THE ROYAL AERONAUTICAL SOCIETY
WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

MONTHLY NOTICES,

NOVEMBER, 1942.

Reduction in Subscriptions.

For some months the JOURNAL has carried a notice drawing attention to the severe shortage of the supply of paper and asking those members who can otherwise see the JOURNAL, apart from the copy to which they are entitled, should consider giving up their copy for the period of the war. The notice added that if a sufficient response was received to the suggestion it would not only have the effect of enabling the JOURNAL to keep closely to the standard it has set, but might have the further effect of enabling some reduction to be made in the subscriptions of those who had helped by giving up their JOURNAL for the war period.

The Council, at their last meeting, reviewed the response to their suggestion and have decided to reduce the 1943 subscriptions of those Fellows, Associate Fellows, Graduates, Companions and Founder Members by 10s. 6d. who give up their JOURNAL for the year. The low subscription at present paid by Students does not permit any reduction to be made. Associates who do not wish to receive the JOURNAL will receive the reduction already laid down in the Rules.

All those members who have already relinquished their JOURNAL and others who do so before Monday, December 14th, 1942, will be notified of the reduction in their subscriptions due on January 1st, 1943.

Advertisements.

The fact that goods made of raw materials in short supply owing to war conditions, are advertised in the Journal, should not be taken as an indication that they are necessarily available for export.

Associate Fellowship Examination, December, 1942.

Those candidates who have entered for the Associate Fellowship Examination on December 15th and 16th, will be sent full particulars direct to their registered addresses.

Society of British Aircraft Constructors' Scholarships.

The Scholarship Selection Committee of the Society of British Aircraft Constructors and the Royal Aeronautical Society have made awards of Society of British Aircraft Constructors' Scholarships to the following:—

Eustace Laurence Goldsmith ... 82, Mount Ephraim, Tunbridge Wells. (Educated at Pope Street School and Colfe's Grammar School.)

Joseph Gilson William McHarry	77, Mary Street, Scunthorpe. (Educated at Frodingham Junior School, Brumby Boys' Senior School and Scunthorpe Technical School.)
Spencer Davidson Meston ...	57, Swilly Road, Plymouth. (Educated at North Prospect Elementary School, Plymouth, and Devonport High School for Boys.)
Denis Roland Murrin	11, Glon View Road, Bromley, Kent. (Educated at Raglan Road Elementary School and Country School for Boys.)

Graduates' and Students' Section.

Members of the Graduates' and Students' Section are invited to the following lectures arranged by the Graduates' Section of the Institution of Automobile Engineers, 12, Hobart Place, London, S.W.1 :—

Sunday, November 15th, 1942, 2.30 p.m.—Talk by Mr. J. Jack on " The Development of the Cross Engine."

Sunday, December 13th, 1942, 2.30 p.m.—Two short papers by Mr. K. B. Hopfinger on " Synthetic Petrol " and " Timber as a Gas Producer Fuel."

Election of Members.

Associate Fellows.—Frank George John Brown, Leonard Turnell Carruthers, Wilhelm Challier, John Webb Clift, Henry George Frankland, John Henry Hawes, Harold Dalton Henniker (from Graduate), Ronald Hewitt, George Maclaren Humphreys, John Parkyn Jeffcock (from Companion), Richard Elliott Leete, Herbert Lloyd, John Marlow, John Kenneth Wilson, William Edward Wright.

Associates.—Edward John Barnes, Henry Patrick Vernon Brown, Edwin James Catt, Richard Cecil Clarke, Maurice Gordon Edgley, George Holdsworth Hurley, Harold Lloyd, Francis John McWhinnie, Jasper Warren Merriam, Basil Parminter Thornber Rosevere, Vernon Skipton.

Graduates.—Peter Nisbet Cunningham (from Student), Ivor Dennis Harnden Gibbins, George William Sapsworth Griffith, Imaduddin Mohammad Khan Malik, Peter Norman.

Additions to the Library.

Pamphlets in italics with location reference following in brackets.
Books marked * or ** may not be taken out on loan.

*B.g.117.—Aircraft Recognition, Part II. By R. Saville-Sneath. Penguin Books, Ltd. 1942. 9d.

*B.g.118.—Aircraft Identification, Part IV. American Monoplanes with the R.A.F. By P. G. Masefield. Temple Press, Ltd. 1942. 2/-.

BB.f.47.—Aircraft Instruments. By W. J. D. Allan. G. Allen and Unwin. 1942. 2/6.

BB.b.101.—*Planes Explained. By Roger Tennant. Argus Press, Ltd.* 1942. 1/-. (PBB.1.a.7.)

BB.c.84.—*Straightening of AZ. 855 Bent Airscrews. (Stencil.) Magnesium Elektron Co., Ltd.* 1942. (Y.8.c.7.)

L.d.78, 79.—Astro-Navigation. By Francis Chichester. Parts 3 and 4. 1941-42. G. Allen and Unwin, Ltd. 2/6 and 4/6 respectively.

**S.b.115.—Pilots of Fighter Command. (64 Portraits.) By Capt. Cuthbert Orde. G. G. Harrap. 1942. 25/-.

TT.a.38.—We Rendezvous at Ten. By "Blake." Victor Gollancz. 1942. 8/6. (Fiction.)

*UU.c.—*National Advisory Committee for Aeronautics, U.S.A. Technical Memoranda*:—

No. 1,025. Self-Ignition and Combustion of Gases. By A. S. Sokolik. (From: Progress of Physical Science, U.S.S.R., Vol. 23, No. 3, 1940.)

No. 1,027. The Formation of Ice on Aircraft. By W. Bleeker. (From: Meteorologische Zeitschrift, Sept., 1932.)

J. Laurence Pritchard, *Secretary and Editor.*

FUNDAMENTALS OF FIGHTER DESIGN.

By F. H. M. Lloyd, A.F.R.Ae.S.

Introduction.

The present trend of fighter design is towards high speeds at greater heights.

For some time it has been apparent that two types of fighter are necessary. Firstly, the small, highly manœuvrable and very fast single-seater fighter with high rate of climb and comparatively short range, and secondly, a larger type for escort duties which is necessarily somewhat slower and less manœuvrable. As in all engineering, and particularly in aircraft engineering, the conclusions which are reached to arrive at a final design never produce an ideal. If this were possible it would only be necessary to consider one type of fighter, for the small single-seater would have the range of the escort fighter, or alternatively the escort fighter would have the speed, manœuvrability and climb of the small single-seater.

It is proposed to examine the case of the small single-seater only, since it is necessary to limit the field of discussion. Further, the purpose of the single-seater fighter is clearly defined and there are numerous types.

The function of a single-seater fighter is to destroy enemy aircraft, which may be bombers, other single-seater fighters or escort fighters. As has been seen recently in the press, fighters are also being used now for ground strafing aerodromes and troops, and for making low level attacks against enemy armoured units and shipping. This low level action has, however, been incidental to their main function of destroying enemy aircraft in the air, and fighters have not been designed in this country especially for ground strafing duties. Before the end of this war we may yet see a third type of fighter designed purely for low level attack on ground and sea targets. This was proved necessary in the last war when the year 1918 saw the arrival on the Western Front of the Sopwith Salamander which was specifically designed as a trench fighter, and which acted in support of ground forces. The Salamander was heavily armoured to protect the pilot and the engine, and had its best performance at low altitude. The design was the result of the successful use of such machines as the Camel for ground strafing, which had only been achieved at the cost of a considerable number of pilots and aircraft. There is a need for low level attack fighters now, and suitably armed they will be more useful than the German Stuka dive bomber, which has been used with such great effect in support of ground forces.

Requirements of a Single-Seater Fighter.

The requirements of a single-seater fighter are high speed, a high ceiling and quick rate of climb, good manœuvrability, powerful armament, small size, slow landing speed, and as long a range as practicable. Unfortunately we find that speed may be obtained at the expense of manœuvrability; powerful armament and small size at the expense of range. Again, greater speeds may be obtained by installing engines of greater power, but as powers increase so engine weights increase and structure weight increases.

With a small aeroplane the increased weight, brought about by fitting an engine of high power and by the strength requirements of high speed, results in such high wing loading that the loss of manœuvrability becomes very marked, and the aeroplane becomes less efficient as a fighting weapon. In order to maintain manœuvrability it is essential to keep the wing loading to a reasonable figure, thereby losing some of the speed we have gained by careful aerodynamic

design and increased power and so arrive at the best compromise for combined speed and manœuvrability. These two requirements must therefore be dealt with as a single issue.

Speed and Manœuvrability.

Desirable Qualities.

The most important qualities in fighting manœuvrability are:—

(1) The pilot must be able to hold a high speed dive with precision and ease.
(2) He must be able to break away quickly from it in the horizontal plane.
(3) His minimum turning radius in the horizontal plane must be as small as possible.

Each of these fighting qualities needs special consideration in design.

The break away, for instance, requires a high rate of bank at high speed under the maximum force which the average pilot can reasonably be expected to apply to the control column, and also good stability and control in the high speed turn at or near the pilot's black-out.

Time to Bank to a Given Angle.

Approximately for a given pilot's force, the time to bank to a given angle for geometrically similar aeroplanes varies theoretically as the fourth power of the span. There is, however, a damping effect in the roll which depends on aspect ratio and rate of roll. The greater the rate of roll the more incidence (and therefore the lift on the down-going wing) is increased, while the lift on the up-going wing is decreased; and the higher the aspect ratio the more marked this effect becomes. So, for a given aspect ratio the difficulty of providing light ailerons varies as the fourth power of the span.

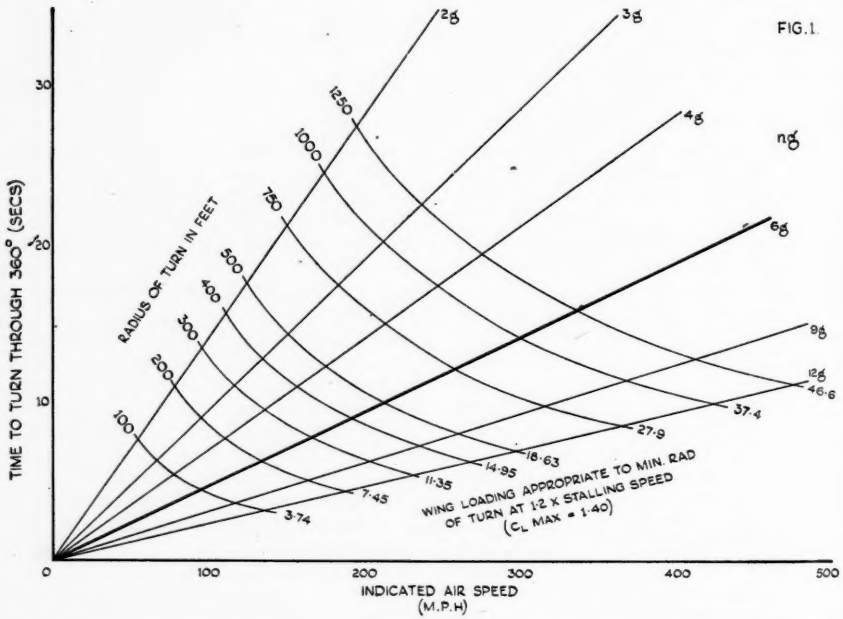
There is also a large variation in aileron heaviness between individual aeroplanes of a given type—hinge moments of ailerons are very sensitive to small protuberances on the control surface as well as to the curvature of the profile. The problem of aileron balance is in fact now so delicate that comparatively small variations make all the difference between good and bad control at high speeds. Much work remains to be done in this direction. Existing data is rather scanty and unreliable, but a serious effort is now being made to achieve a standard aileron performance by laying down a minimum size and area for ailerons. Since the standard of workmanship in wartime is bound to deteriorate owing to the dilution of skilled labour with semi-skilled and unskilled labour, the results of this effort may prove to be misleading.

In spite of the above evidence it is known that manœuvrability varies considerably with speed and loading, and although theory will be of use when aileron design and manufacture are improved it cannot at present be used with any certainty.

Time to Turn and Radius of Turn.

Once the aeroplane has banked to a given angle and is turning steadily in a horizontal plane, the aileron control effectiveness is no longer the decisive factor. The degree of manœuvrability in this condition is merely inversely proportional to the wing loading. Thus for any given wing loading there is a definite minimum radius of turn, no matter how fast or how slow this turn is flown. There is only one limitation, which is a physical one; the faster a turn of minimum radius is flown, the higher becomes the acceleration to which pilot and aeroplane is subjected, and there is a limit to what either can stand. High factors on the aeroplane can be allowed for in the design stage, but a highly trained and physically fit pilot who is used to performing aerobatics regularly can only withstand an acceleration of about 6 g. without blacking out. Now

we have learnt in this war that the fighter aeroplane with the higher wing loading cannot stay and fight on even terms in a " dog-fight " with a fighter of lower wing loading. In the Battle of Britain the more lightly loaded Hurricanes and Spitfires with wing loading about 25 lb./sq. ft. had the advantage over the Me. 109 with a wing loading of 32 lb./sq. ft. As the Spitfire was also faster than the Me. 109, our superiority in fighter design was unquestionable. The object then to be attained is the production of a fighter with both superior speed and lower wing loading than the enemy fighter. For speed we need not only clean aerodynamic design but also engines of greater power and airframes of small size. Higher powered engines mean more weight, and small size means making the wing area as small as possible. The attainment of more speed must therefore result in an increase in wing loading, and consequently in a reduction of manœuvrability in the turn. In designing the Fw. 190 the Germans called



a new tune. In this design the wing loading is 42 lb-/sq. ft., and manœuvrability in the turn was sacrificed for speed and quick rate of climb. In combat against fighters of inferior speed and climb performance, but better manœuvrability, they can gain height by their superior climb, then dive, open fire at short range, and climb away again. The advantage then which the aeroplane with the lower wing loading possesses in turning manœuvrability cannot be used offensively, but this does not mean to say that wing loading can now be neglected. An aeroplane with low power loading will have good climbing performance and if we can keep the all-up weight within reasonable bounds by limiting the equipment and by careful structural design, we will also reduce the wing loading for a given wing area. It must be remembered that of two fighters with approximately equal speed and climb performance the one with greater manœuvrability will always have the advantage. Low wing loading is one way in which this may be obtained, but for good rolling manœuvrability we require small span, and a combination of the two leads to the conclusion that for manœuvrability

in general a low aspect ratio is a desirable feature. It will be shown later, however, that this would have an adverse effect on range on ceiling and on climb near the ceiling. The other way in which manœuvrability can be gained in the turn is by increasing the resistance of pilots to high accelerations. This is a medical problem, and all that can be said here is that some success has been achieved in this direction, and that recent experiments have shown great promise of a considerable increase in the number of " g " which pilots will be able to withstand with artificial aids.

Fig. 1 summarises the effect of wing loading on radius of turn, and of " g " on the time taken to make the turn. Of course, it has been necessary to make some assumptions which do not always apply. For instance, the maximum lift coefficient has been assumed to be 1.4, and the minimum speed at which a steady turn can be held has been taken to be 1.2 times the stalling speed at the appropriate " g." Against the curves of each radius of turn is shown the wing loading which then permits a turn of that minimum radius. An aeroplane with wing loading 18.63 lb./sq. ft., for example, has a minimum radius of turn of 500 ft., but a complete 360° turn cannot be made in 7 seconds since this would result in 12 g. Not only is this acceleration beyond the physical powers of the pilot, but no aeroplane is designed up to this strength. The minimum time for the turn is about 10 seconds at 6 g., when the speed in the turn would be 210 m.p.h. I.A.S. A turn made at 300 m.p.h. would take $14\frac{1}{4}$ secs. at 6 g. and on a radius of 1,000 ft., which is the same as the minimum radius and time to turn an aeroplane with a wing loading of 37.4 lb./sq. ft.

It can be safely predicted that the tendency in future will be towards higher wing loading and higher speeds in the turn, resulting in possibly as much as 8 or 10 g. The question of manœuvrability will have to be watched very carefully, and wing loading kept as low as practicable, while some means will have to be found to make the pilot more resistant to high accelerations.

Speed.

Having decided on a given wing loading such as will permit the fighter to manœuvre on even terms with other aeroplanes of its class, attention must be paid to obtaining the maximum possible speed at that particular loading.

Among the factors we have to consider are the following :—

Aerodynamic cleanliness.
Effect of aspect ratio.
Airscrew design.
Low cooling drag.
Exhaust ejection, etc.

1. Aerodynamic Cleanliness.

The complete reversion to the cantilever monoplane type with retractable undercarriage has done everything that can be done to reduce drag from the point of view of the general layout of the design, and as a result it has become increasingly evident how much attention has to be paid to detail. Not only are careful fairing and exact fit of doors and panels of importance, but increasing attention has to be paid to the effect of surface roughness on drag. Recent tests on an aerofoil of 8 in. chord at high Reynolds number (about 7 millions) at the N.P.L. have shown that excrescences on the surface of about 0.0004 in. result in an increase of drag of some 32 per cent. over that of a perfectly smooth aerofoil, while excrescences of 0.001 cause an increase over 70 per cent. These roughnesses correspond to excrescences of 0.004 and 0.01 inch respectively on a full-scale wing of about 7 ft. chord, which is not much rougher than many fabric covered wings. It was also found that by roughening only the forward half about two-thirds of the drag was obtained, and by roughening only the rear half one-third of the total drag was measured. These results have an obvious

bearing on aircraft construction. In addition to keeping a smooth surface near the leading edge where flush riveting is normally employed, advantage is also gained by retaining a smooth surface to the trailing edge.

At a Reynolds number of ten millions, if the chord is 8 feet, the permissible height of the excrescences must not exceed 0.001 inch. The same principle also applies to the fuselage.

2. Aspect Ratio.

The aspect ratio is the ratio of the square of the span to the wing area. Thus the greater the span for a given wing area, the greater the aspect ratio.

The effect of aspect ratio on drag is as follows:—

A high aspect ratio decreases the induced drag, particularly at high lift coefficients. The effect is not so marked at high speeds. A high aspect ratio, however, increases the structure weight, and also has an adverse effect on rolling manœuvrability. On the other hand, from the point of view of climb, ceiling and range, a high aspect ratio is a desirable feature. It is therefore necessary again to strike a compromise, and usually the aspect ratio of a fighter is between $5\frac{1}{2}$ and 7.

3. Airscrew Design.

The problem of absorbing the power output of modern engines at high altitudes, and converting the maximum power into thrust by means of an airscrew is one which is receiving much attention. If compressibility effects were absent, an airscrew of normal solidity could absorb these powers efficiently provided its diameter were large. This increase might be possible with larger type aircraft, but in the case of a single-seater fighter the diameter is limited by ground clearance. In fact, from the point of view of undercarriage design and weight and size of landing gear, it is desirable to keep the diameter within reasonable limits. Again, if compressibility could be neglected, power could be absorbed by increasing the r.p.m. Owing to compressibility, however, tip losses are so large that such increases in diameter and r.p.m. are impossible.

The only remaining alternative is to increase the solidity. This may be done in several ways.

(1) The blade width may be increased, keeping the number of blades constant. There is a limit to this, as these wide blades produce a high centrifugal twisting moment which has to be taken out by the pitch changing mechanism. Any further increase on existing widths will necessitate redesigned hubs.

(2) The number of blades can be increased. The majority of aircraft at the moment are fitted with three-bladed airscrews, but higher powers will require combinations of four, five or six blades. The possibility of using contra-rotating airscrews in tandem also arises, since in addition to its ability to absorb power this arrangement has certain other advantages. At present six blades will be sufficient to absorb the power efficiently, but as powers increase it will be possible to increase the solidity still further by having eight blades (two four-bladers in tandem).

Advantages of the contra-rotating airscrew are as follows:—

(i) The take-off thrust is increased over that of a single airscrew of the same solidity. The reason for this is that the fluctuating incidence of the blade sections, due to interference between blades, delays the stall and thus puts up the thrust.

(ii) For aircraft fitted with more powerful engines a contra-rotating airscrew enables the airscrew diameter to be reduced with a consequent reduction in tip losses, and a reduction in the length of undercarriage required.

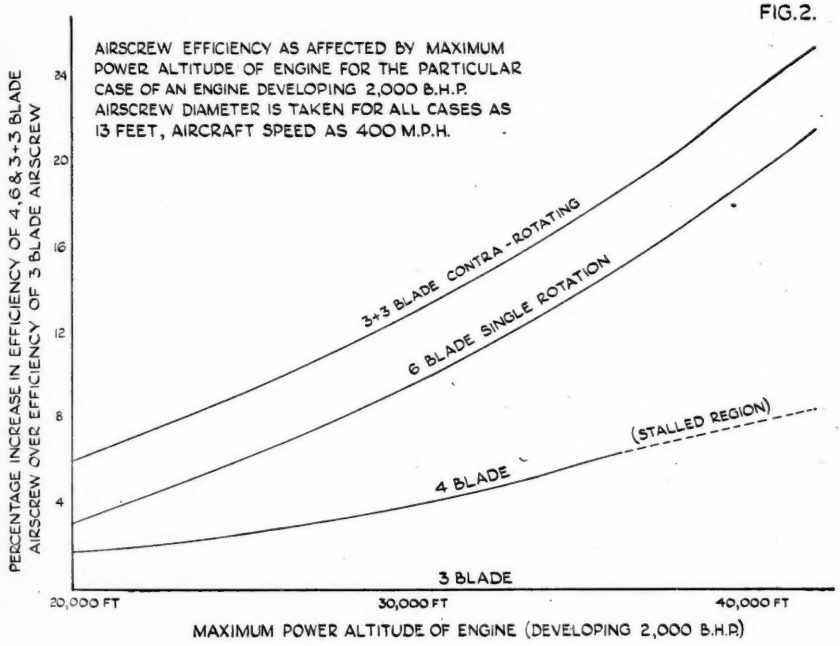
(iii) In order to keep tip losses low, a low gear ratio is required on high speed aircraft at great heights. If the diameter is reduced with a normal single airscrew, the result would be a severe falling off in take-

off thrust, but with a contra-rotating airscrew the take-off thrust will still be good because of the effects mentioned in (i) above.

(iv) The contra-rotating airscrew produces a symmetrical flow, eliminating many control troubles. Airscrew torque and gyroscopic couples are neutralised; swing at take-off disappears, and control in the air is simplified. While we have at present not much experience with this type of airscrew, it is also claimed that the removal of the slipstream rotation over the body and wing roots will result in a reduction of drag. Additional thrust is also obtained since there is no energy lost in rotating the slipstream.

It might be claimed that a single six-bladed airscrew would produce all the advantages of the contra-rotating airscrew, but the torque reaction and gyroscopic couple would be very large.

FIG. 2.


AIRSCREW EFFICIENCY AS AFFECTED BY MAXIMUM POWER ALTITUDE OF ENGINE FOR THE PARTICULAR CASE OF AN ENGINE DEVELOPING 2,000 B.H.P. AIRSCREW DIAMETER IS TAKEN FOR ALL CASES AS 13 FEET, AIRCRAFT SPEED AS 400 M.P.H.
PERCENTAGE INCREASE IN EFFICIENCY OF 4, 6 & 3+3 BLADE AIRSCREW OVER EFFICIENCY OF 3 BLADE AIRSCREW
24
20
16
12
8
4
3+3 BLADE CONTRA-ROTATING
6 BLADE SINGLE ROTATION
(STALLED REGION)
4 BLADE
3 BLADE
20,000 FT
30,000 FT
40,000 FT
MAXIMUM POWER ALTITUDE OF ENGINE (DEVELOPING 2,000 B.H.P.)

There are, of course, disadvantages in fitting a contra-rotating airscrew, but these are outweighed by the advantages.

Disadvantages are:—

(*a*) Additional weight.
(*b*) Additional complication and maintenance troubles.
(*c*) Possible vibration due to interference between blades.
(*d*) The difficulty of designing a " clean " spinner.

As a rough indication of the effect on performance of a single-seater fighter the following improvements may be expected by fitting a contra-rotating airscrew of six blades instead of a single three-bladed airscrew.

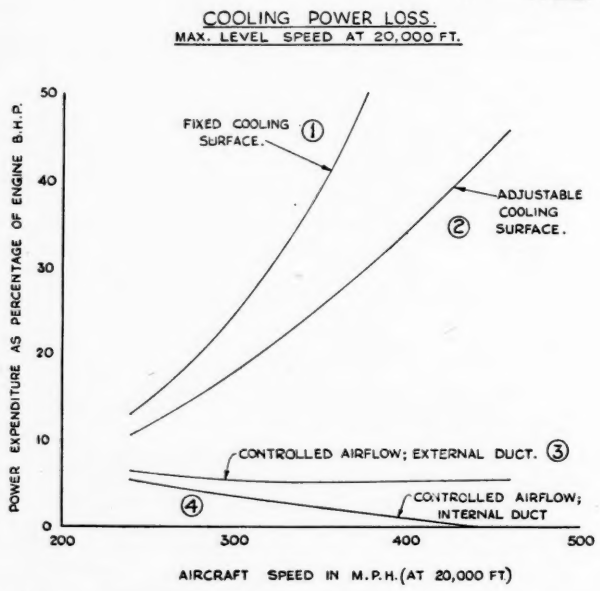
The increase in maximum level speed of 450 m.p.h. fighter at 25,000 feet will be approximately 10 m.p.h., while the time to climb to 35,000 feet will be reduced by about one minute. With maximum power altitude of 35,000 feet the speed

would be increased by 18 m.p.h., and the time to climb to 40,000 feet reduced by about $3\frac{1}{2}$ minutes. The take-off run in each case will also be greatly improved.

Fig. 2 illustrates the increase in percentage airscrew efficiency over that of a three-bladed airscrew obtained by fitting, a four-blader, a six-blader single rotation, or a six-blader contra-rotating airscrew. This illustrates that it becomes essential to fit a contra-rotating airscrew to obtain maximum performance at very high altitudes. It can safely be predicted that as maximum power altitudes of engines increase with more efficient supercharging, designers will be forced into the use of contra-rotating airscrews of six or eight blades.

This curve illustrates conditions for a particular engine developing 2,000 b.h.p. at varying maximum power altitude, and constant forward speed. The airscrew diameter is 13 feet in each case, and current blade width is assumed ($J = V/nD = 3$).

FIG. 3.



4. Cooling System.

The cooling of an aeroplane engine necessitates the exposure of a large heated surface to the airstream, and, although the dissipation increases as the square of the airspeed, the power expenditure increases as the cube.

This means that if an air-cooled engine or water radiator of fixed size is exposed to the free airstream, the power expenditure will increase as the cube of the aircraft speed as shown by curve (1) of Fig. 3. This method is only suitable for aircraft whose top speed is not more than 200 m.p.h., the power expenditure being prohibitive above this speed. Also, as the heat dissipation increases as the square of the airspeed, the engine will be over-cooled at top speed if it is adequately cooled at climbing speed. This may be overcome in the case of the water radiator by making it retractable; this is to have an adjustable surface, so that in retracting the radiator the power expenditure will be decreased, varying only as the square of the aircraft speed, see curve (2).

For speeds above 250 m.p.h. it is more satisfactory, indeed necessary, to adjust the airflow and leave the cooling surface fixed.

This is the modern low-velocity system. In this method the cooling air is gradually expanded in a suitably shaped duct, without loss of energy, and so reduced in velocity. It is then passed over the cylinder fins or radiator, as the case may be, and, due to its relatively high pressure, some of the heat dissipated is converted into useful thrust which increases with aircraft speed until at about 400 m.p.h. it nullifies the internal drag of the system. The cooling flow is controlled by an adjustable exit area to the duct which exhausts the air at the correct external stream density. Curve (3) shows the cooling power expenditure for an ordinary air-cooled engine or an external cowled radiator and is constant at about 5 per cent. up to a speed of 450 m.p.h. Above this speed the external form drag is liable to increase rapidly due to the onset of compressibility, and it is advisable to suppress the air-cooled engine or radiator to within the wing. This latter method results in zero cooling power expenditure at 450 m.p.h. and theoretically augments the engine power as this speed increases; see curve (4).

5. Intakes and Exhausts.

Although intakes and exhausts are two separate problems, they are both amenable to the same type of momentum and energy analysis. One is the problem of obtaining the maximum carburettor supercharge pressure with the minimum aerodynamic drag, and the other is the problem of discharging the waste exhaust gases so as to obtain the maximum useful thrust having due regard to the effects of exhaust back pressure on the engine power.

(i) Intakes.

All petrol engines consume about 2 lb. of air per second for every 1,000 b.h.p., and this air has to be picked up from rest and given the same forward speed as the aeroplane. The air then has to be expanded to the full pitot pressure at the carburettor. The momentum drag due to picking up the air from rest is of course unavoidable, but aerodynamic drag may be reduced to a minimum by gradual expansion in the intake. This calls for a very long gradually expanding intake, which unfortunately is frequently impossible to obtain owing to structural complications. In some installations fairly rapidly expanding intakes are fitted with diffuser vanes and give an engine power nearly equal to the maximum obtainable with an ideal intake, but at the cost of a certain amount of aerodynamic drag. The main point to remember is that carefully faired or streamlined intakes give a maximum carburettor pressure with a nett drag very little greater than that associated with the change in momentum of the air. The most important feature of this is that by providing the full pitot pressure at the carburettor it is possible to increase the maximum power altitude of the engine above its rated altitude. With an ideal intake this is of the order of 4,500 feet at 20,000 feet. Ideally the intake should be of relatively large area situated in a stagnation region on the aeroplane such as the leading edge of a wing. The entry loss would be negligible so that almost full pitot pressure will be available at the carburettor, and the drag would not exceed that due to the change of momentum of the air.

(ii) Exhausts.

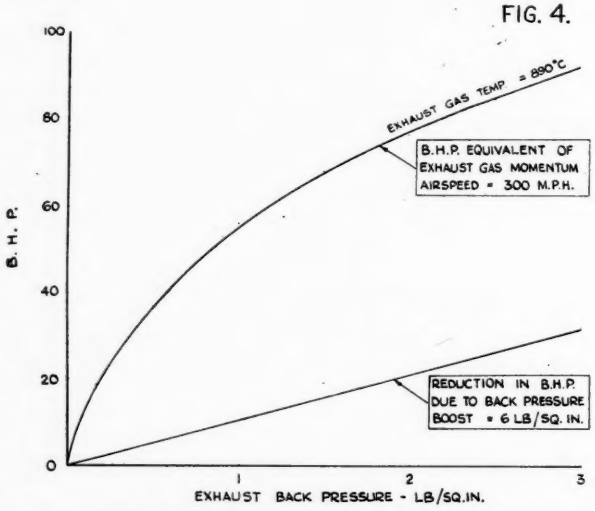
The recovery of useful work from the exhaust gases of an engine may be achieved by ejecting the gases backwards at high velocity. With stub exhaust pipes the velocity with which the gases are ejected is of the order of 2,000-3,500 ft./sec. for highly supercharged engines at about 15,000 ft., but it would be impossible to deflect these gases backwards at this velocity without considerable increase in back pressure. Increased back pressure must be avoided as far as possible because it decreases the volumetric efficiency of the engine. In other words, the effect of back pressure is to increase the mass of residual

exhaust products left in the cylinder when the exhaust valve closes, and this affects the power output.

The object then is to design ejector manifolds which give high ejection velocities with the minimum increase in back pressure. It can be shown theoretically that velocities of about 1,200 ft./sec. can be obtained with an exhaust back pressure of about 2 lb./sq. in.; with high speed aircraft, the power equivalent of the exhaust gas momentum is large compared with the reduction due to the increase of back pressure.

Fig. 4 taken from an unpublished report by de Paravicini applies to an engine with 6 lb./sq. in., boost pressure at 15,000 feet and shows that the reduction in b.h.p. due to back pressure is small compared to the power equivalent of the exhaust gas momentum. For instance, at 300 m.p.h. with an exhaust back

FIG. 4.



B.H.P. EQUIVALENT OF EXHAUST GAS MOMENTUM

1000 B.H.P. ENGINE : HEIGHT 15,000 FT.

pressure of 2 lb./sq. in., a power increase of 56 b.h.p. should be obtained. If the exhaust gas temperature of 890°C. is too low, the power increase is underestimated slightly. For example, for a temperature of 1,000°C., the gain in power is 60 b.h.p. under the above conditions.

Choice of an Aerofoil Section.

We have now decided on the wing loading and plan form of the wing, and have touched on a few of the methods by which additional speed may be gained without adversely affecting other aspects of performance.

Up till recently compressibility effects have not been serious and any aerofoil section with a low minimum drag and low moment coefficient has been satisfactory. As speeds have increased we now have to give consideration to compressibility, and have to use symmetrical of very low cambered aerofoils with maximum thickness about 40 per cent. of the chord. This does not help installation or structural problems, since for the best solution of these plenty of thickness well forward is required.

Thickness should be as little as possible, especially as speeds rise, but here structural and equipment problems force the thickness up above the best figure. Fuel tanks, guns and undercarriages have to be stowed, and as wing areas get less and fuel consumption increases with higher powered engines so the thickness is forced up.

If the root chord is kept large, the thickness/chord ratio is kept reasonably low, and this leads to the issue of an elliptical wing. In general, if the thickness/chord ratio does not exceed 18 per cent. at the root and 12 per cent. at the tip, no serious loss in speed will be experienced up to 400 m.p.h.

FIG. 5.

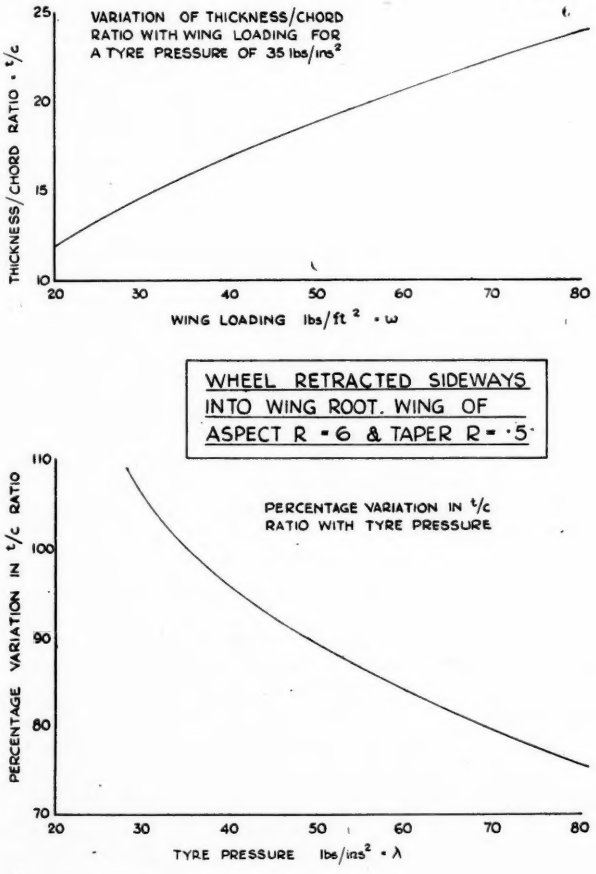


Fig. 5 shows the effect of wing loading on the root thickness-chord ratio with a standard tyre pressure of 35 lb./sq. in., *e.g.*, for a wing loading of 40 lb./ft.² the minimum thickness/chord ratio is 17 per cent. The lower curve shows that to reduce this thickness/chord ratio to 15 per cent. the tyre pressure will have to be increased to 52 lb./in.². Higher tyre pressures may be used in future to give smaller wheels, which will allow the design of a more efficient and lighter wing

structure. Nevertheless, it must be remembered that small wheels restrict the operation of the aircraft to good aerodromes with prepared runways.

Aerofoil Drag.

The total drag of an aerofoil is made up of (i) induced drag, (ii) profile drag, and (iii) drag due to compressibility burble.

(i) Induced drag is primarily a function of the plan form of the wing for a given speed and wing loading, and is not influenced by the aerofoil profile.

(ii) Profile drag, for a given speed and section lift coefficient, is a function of the profile shape and surface roughness, and can be subdivided into skin friction drag and form drag.

(*a*) Skin friction drag depends on the position of the point of transition from laminar to turbulent flow in the boundary layer, local surface velocities and pressure gradients, the degree of roughness and the degree and scale of turbulence in the airstream, all of which are to an extent inter-related.

In designing the profile drag the object is to maintain laminar flow over as large an area as possible, by reducing local surface velocities and positive pressure gradients to a minimum. Experiments in a high speed wind tunnel indicate that the maximum ordinate should be placed at 0.40-0.45 of the chord to get the best result in this direction, and that the section should be thin resulting in a small leading edge radius.

(*b*) Form drag is caused by the distortion of the flow around the section due to the viscosity of the air. Form drag can be reduced by reducing the thickness of the aerofoil, and by careful design of the profile aft of the maximum ordinate so as to avoid large positive pressure gradients.

(iii) Drag Due to Compressibility Burble.

If at any point on the aerofoil surface, where the pressure gradient is positive, the local velocity of the air exceeds the local velocity of sound, a shock wave is formed, the effects of which are characterised by loss of lift and very large increases in drag and pitching moment.

The profile must therefore satisfy the following requirements:—

(*a*) The local induced velocities, and consequently negative pressure coefficients, must be as small as possible.

(*b*) A negative pressure gradient should be maintained over as large a part of the profile as possible.

(*c*) There should be no large positive pressure gradients.

At the speeds and Reynolds numbers of current designs it is difficult to maintain the boundary layer laminar aft of 0.40 chord whatever the nature of the pressure gradients over the surface, due to the extreme thinness and sensitivity of the layer. With the maximum thickness at about 40 per cent. of the chord, the leading edge radius is then small, which is essential for the maintenance of the correct pressure distribution at low incidence by fixing the stagnation point at the leading edge. This leads to some sacrifice in the stalling qualities of the profile, and to avoid tip-stalling on highly tapered wings it may be necessary to move the maximum ordinate forward slightly towards the tip.

The way in which a wing stalls depends primarily on three main factors:—

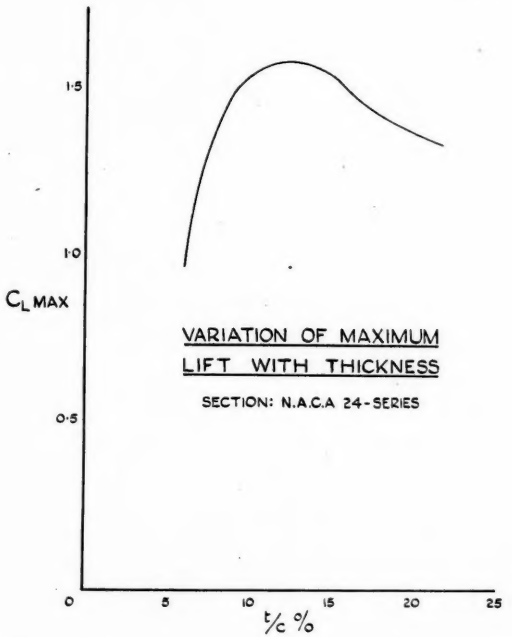
(i) The wing section.
(ii) The wing twist.
(iii) The wing plan form.

(i) The maximum lift which an aerofoil section will develop before stalling depends upon its thickness, general basic shape and camber; in the limited ranges in which we are normally forced to work from other considerations,

thickness appears to be the most important of these variables. For most normal sections the optimum thickness appears to be about 12 per cent. (see Fig. 6). Thinner sections stall by a " front stall," which is usually sudden and vicious in character; thicker sections stall first towards the rear, and the stall is usually gentler.

(ii) Since the point at which a wing stalls is dependent upon its angle of incidence, the position along the wing span where stalling first appears can obviously be controlled by twisting the wing, *i.e.*, by " washout " where the angle of incidence decreases towards the tip so that the root will stall first, and " wash-in " where the reverse occurs. This method of control is, however, not satisfactory for high speed aircraft, as at the low lift coefficients of high speed flight the drag is always greater than that of an untwisted drag.

FIG. 6.



(iii) An untwisted elliptic wing formed of similar sections of the same thickness/chord ratio will stall throughout its span at the same time. The stall on wings of other shapes (*e.g.*, straight tapered wings) follows no hard and fast rule, although the general tendencies are illustrated on Fig. 7.

It is not desirable to design a wing to stall across its whole span at the same time, as the stall will usually occur suddenly and without warning. It is better to make the stall spread from the root outwards, as such a stall will be gentle and not accompanied by sudden vicious wing dropping or lack of aileron control.

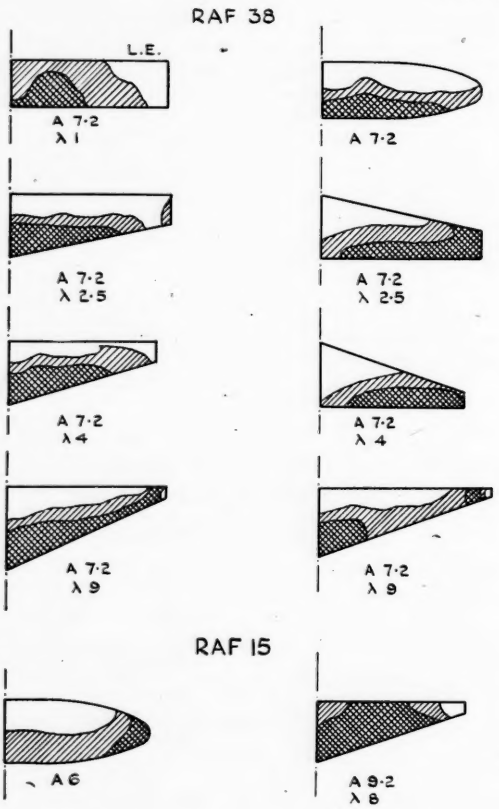
Body Shape.

The wing being fixed, the next problem is that of the body shape. This should be the smallest possible streamline shape which can enclose the engine and provide space for the pilot and equipment. The body form should be such that

the rate of change of curvature along it is small and continuous, otherwise breakdown of flow will take place, which will set up higher drag.

Of necessity, the pilot's cabin breaks this shape and must be kept as small as possible, free from sharp corners and faired into the body with easy curves. Here the operational requirements are up against the aerodynamic requirements. Good view necessitates a deep windscreen with a flat front, but at high speeds both the flat area and the height of the windscreen must be kept very small.

FIG. 7.



A possible source of much drag is interference between the various units, and careful tests must be made on any fast aeroplane to eliminate this. Wing-body interference is the biggest of these effects. A mid-wing position gives less chance of interference than any other, but this position is rarely possible for structural reasons and because the length of the undercarriage has to be such as to give the necessary ground clearance for the airscrew. A low wing is therefore used, when careful filleting is required both at the leading and trailing edge junctions. Equal care has to be taken in fairing in the tail unit and any other excrescences however small.

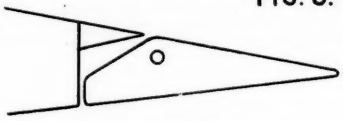
A further source of drag is that caused when air flows through the structure from areas of one pressure to those of a lower pressure. These flows are known

as "leaks." All openings must therefore be carefully sealed from the main interior. Examples of such leaks are from the spinner to the exhaust ports, and from the wheel well into the body. Particular care must be taken to ensure the proper fit of panels, access doors, etc., also to mount them on a structure that is stiff and will not deflect under air loads.

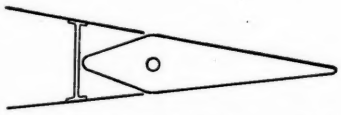
Having considered the layout of the design from the point of view of speed, climb and manœuvrability there are various other factors which have to be taken into account. Final design prominence being given to speed the remaining qualities are generally satisfied as far as possible. A reasonable landing speed is required, the machine must be light on the controls yet stable enough to be a steady gun platform. An adequate weight of armament must be provided, the service ceiling must be high, and the range reasonably long.

BALANCED CONTROL SURFACES.

FIG. 8.



FRISE TYPE AILERON



SET-BACK HINGE TYPE CONTROL

LANDING SPEED.

Landing speeds can usually be kept down to reasonable values by the use of slow landing flaps. To save complication these have in the past usually been of the split type. For wing loadings higher than 30 lb./sq. ft., however, it is possibly worth giving consideration to flaps giving both higher lift and drag characteristics. These may upset landing characteristics due to large change of trim, however, and some caution is necessary, but a maximum lift coefficient of 2.5 is not unusual.

If possible slots should be avoided, because, even with the best possible installation, the portion of the wing to which they are fitted has a higher drag than if slots were not fitted.

STABILITY AND CONTROL.

The most important point under the heading of Stability and Control is that of keeping down the forces which the pilot has to exert when manœuvring. To get this some form of balanced control has to be used.

Fig. 8 illustrates two types of aerodynamically balanced controls.

In spite of its known troubles the Frise aileron is still probably the best all round type, though combined differential linkage and tab control promises good results. There should be as small a gap as possible, between the leading edge of the aileron and the wing, in order to increase the pressure difference

between the top and bottom surfaces, and the percentage aileron area to wing area should be at least 7 per cent.

For elevators and rudders a set-back hinge gives the best results. If this is shrouded the balancing is not affected but the drag is reduced. A small trimming tab adjustable in flight should be provided on the elevators to deal with changes of trim, and also on the rudder to reduce rudder loads on climb when a contra-rotating airscrew is not used.

The horn type of balance is dangerous at high speeds because of the very high loads which can be set up on the nose of the balance.

The tail plane volume must be such as just to give longitudinal stability over the whole range of movement of the centre of gravity, yet at the same time not too large because the forces on the elevator would then be increased when manœuvring. It must be remembered that if an aeroplane is just stable at sea level the centre of gravity has to be about 5 per cent. of the mean chord further forward to give stability at 35,000 ft.

Enough dihedral should be given to the main planes to counteract the adverse effects of taper on rolling stability. If the taper is not excessive a mean overall dihedral between 3° and 5° is sufficient for a low-wing monoplane.

The size of the fin and rudder should be such as to give good directional stability when climbing and cruising.

Climb and Ceiling.

When once the all-up weight and wing loading are fixed, climb becomes largely a motor and airscrew problem. Briefly, the power loading should be kept as low as possible, and a constant speed airscrew with a wide range of blade angle should be used in conjunction with a motor which has a two-speed or multi-stage supercharger, and as high a maximum power altitude as possible. An analysis of the factors affecting absolute ceiling which is affected in the same way as climb, gives a clear picture of the magnitude of the effect of each variable.

Above 36,000 ft., a 1 per cent. increase in each variable has the following effect on absolute ceiling:—

1% increase in	all-up weight	gives 200 ft.	loss in ceiling.
,, ,,	overall drag	,, 30 ft.	loss in ceiling.
,, ,,	interference factor ...	,, 100 ft.	loss in ceiling.
,, ,,	span	,, 200 ft.	gain in ceiling.
,, ,,	b.h.p.	,, 130 ft.	gain in ceiling.
,, ,,	propulsive efficiency ...	,, 130 ft.	gain in ceiling.

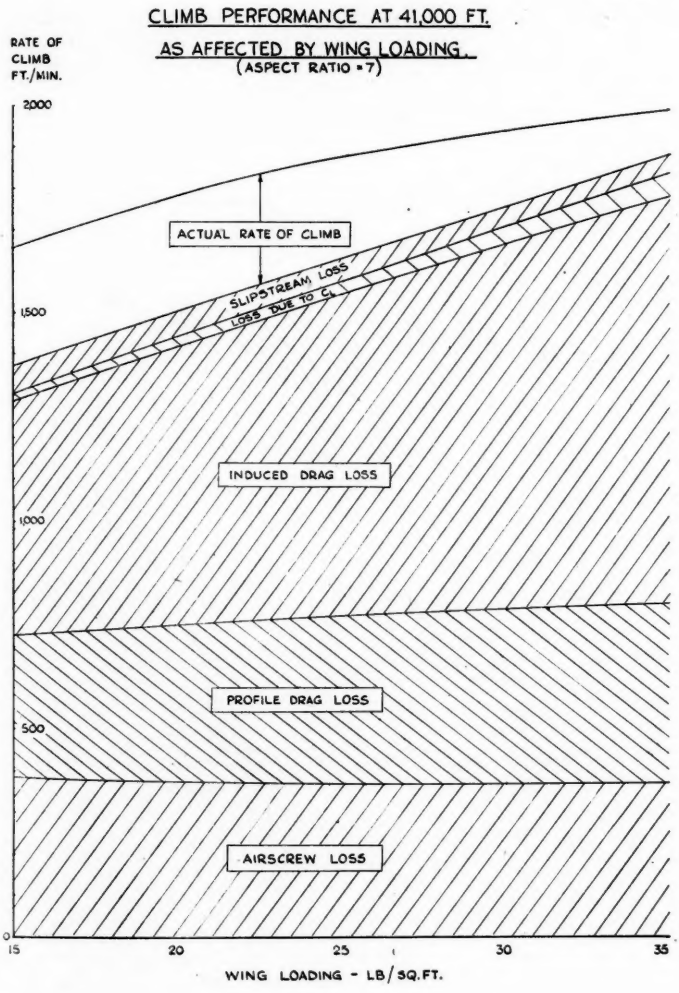
Fig. 9 illustrates the way in which climb performance near the ceiling is affected by wing loading and also by the various components of the aeroplane. The curve was prepared in the following way:—

A standard fighter of wing loading 35.5 lb./ft.^{2}, aspect ratio 7, and power loading at 41,000 ft. 16.55 lbs./b.h.p., was assumed. Optimum rates of climb were then calculated for various wing loadings. Amongst other things, allowance was made for the variation in weight and drag with variation in wing loading, and for the variation in airscrew efficiency with forward speed; the results therefore apply to strictly comparable design alternatives.

It can be seen that the actual rate of climb is really a small difference between two large quantities. The first quantity is the maximum available rate of climb, *i.e.*, that rate of climb that would be obtained supposing that the entire b.h.p. of the engine were devoted to lifting up the aeroplane; this is in fact the reciprocal of the power loading expressed in the appropriate units. The second quantity consists of the rate of climb lost due to part of the b.h.p. being required to fly the aeroplane at a certain forward speed, its optimum climbing speed; this consists of the sum of a number of losses as shown. Ejector exhaust thrust, cooling drag and thrust and air intake drag have not been included as it

has been found that for aeroplanes of the type considered, the nett result is very small. The figure shows the great importance of designing to as low a power loading as possible to obtain good climb performance. Further, since the induced drag loss is the largest loss, it follows that the span loading should be kept as small as possible from the point of view of climb.

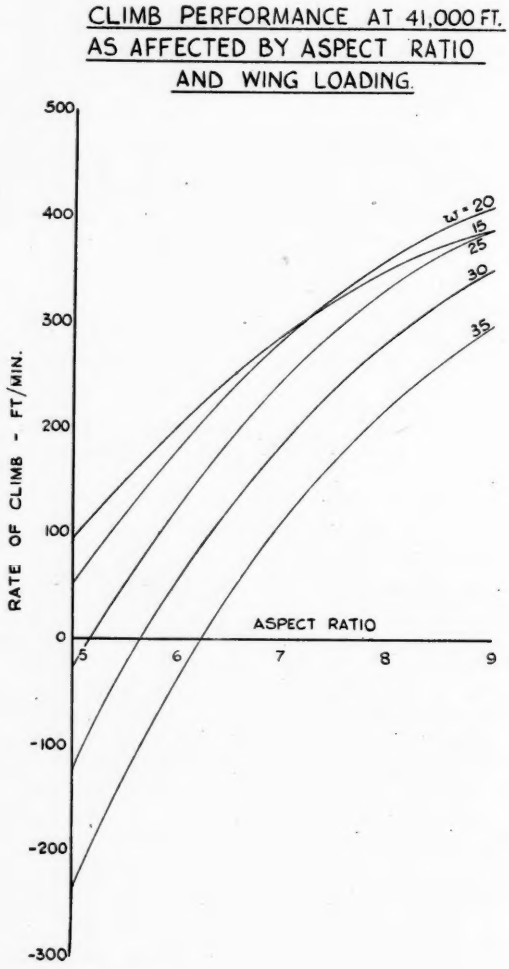
FIG. 9.



This is illustrated more clearly in Fig. 10, which shows the rate of climb at 41,000 ft. for various wing loadings and aspect ratios. This shows how the rate of climb increases as the wing loading and span loading are decreased. There is a limit to this method of increasing climb and ceiling; it is seen that the 15 lb./sq. ft. wing loading curve crosses over the curve of 20 lb./sq. ft.,

wing loading at aspect ratio 7.2. This is because the increase in wing area and span increases the wing weight, and consequently the all-up weight of the aeroplane, which, of course, reduces the climb when carried to an extreme. It is also necessary to remember that for good rolling manœuvrability a low aspect ratio is desirable.

FIG. 10.



RANGE.

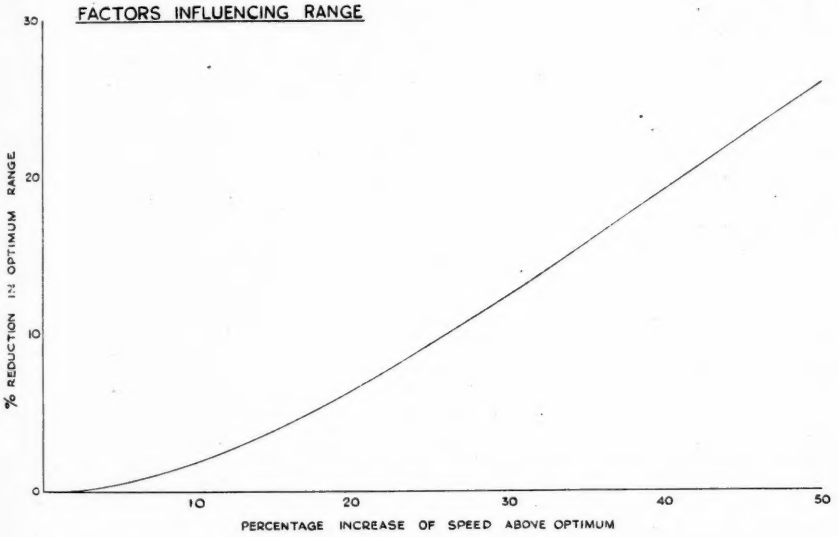
It is important to give a fighter as great a range as possible and the logical way of doing this is to carry as much fuel as possible. Hitherto we have been required to carry all fuel in the wings as far as possible, but in addition the armament has to be carried in the wings and the undercarriage has to be

retracted. The advantages of thin wings for high speed fighters have already been explained, so that available space for fuel tanks is necessarily restricted. In fact every other factor of fighter design militates against long range. Petrol tanks have to be made self-sealing, which also reduces capacity. To the writer, it now appears preferable to carry the main portion of the fuel in the fuselage. Not only is the vulnerable area of the aeroplane reduced, but the fuel system can be very much simpler and lighter and more easily protected.

The effect of various factors having a bearing on range are as follows:—

1%	increase in	propulsive efficiency	...	gives	1%	increase in	range.
1%	,,	span		,,	1%	,,	,,
1%	,,	all-up weight		,,	1%	decrease	,,
1%	,,	interference factor ...		,,	½%	,,	,,
1%	,,	overall drag		,,	½%	,,	,,

FIG. 11.



The greatest range is, of course, obtained when flying at a certain optimum speed throughout the whole flight. Any increase over this speed will reduce the range, so that when range is calculated it is usual to allow for a certain period at full throttle, during which fighting manœuvres may be carried out.

The percentage loss in maximum range due to flying at a speed greater than the optimum is given in Fig. 11.

Structural Problems.

Because of the high speeds now reached and still higher speeds expected, the stiffness of the structure has become as important as the strength. Lack of space forbids a detailed discussion on structural problems, but to conclude, a word might be said about wing structures and one or two general problems.

The ideal wing structure would be one in which a suitably reinforced skin took all the bending and torsion loads and light web members took the shear. But gun doors, wheel wells, holes for tanks, and attachments for the concentrated loads from the undercarriage make this impossible, so that the fighter

wing usually ends up a very mixed type of structure. For the sake of ease of maintenance, and to reduce transport sizes to the minimum, we are required to make each wing detachable from the fuselage, and the joints to take the concentrated loads from the wing on to the fuselage are very heavy.

There are two ways of attacking the wing structure problem. The first is to build the basic monocoque just described and to cut holes in it where necessary, and reinforce the edges of these holes strongly. Stiffness drops considerably when holes are cut in the monocoque, yet this method of construction probably gives the stiffest wing. Its disadvantages are that the holes must be small, since large holes weaken the structure too much, which makes guns and ammunition boxes inaccessible. This is a serious trouble in a fighter, and also makes jigging and construction very difficult.

The other method is directly opposite. This is to build a structure round each of the openings, the covers of which can then be made readily detachable as they are no longer part of the structure. This method gives probably less stiffness and is certainly somewhat heavier than the monocoque method. Its advantages in the case of the fighter, are that guns, undercarriage gears and damaged tanks can be replaced easily and quickly.

This type of construction is usually the two spar type which makes fuselage attachments easy and gives strong points for jigging, making interchangeability easier.

Another form of construction is to make use of the leading edge of the wing as a D-spar and put the equipment behind the spar.

In practice a combination of all three types may be used. Outboard of the equipment the wing will be pure monocoque, while inboard a combination of the two-spar wing and the D-spar may be used.

Stressed skin construction follows the usual lines. Stringers are flush riveted to the skin. When extruded sections are used for spars they should be of the strongest available light alloy in order to keep the weight down.

It is interesting to compare the wing structure of the F.W. 190 with past British practice. In this German fighter all fuel is carried in the fuselage, and the wheels are very small with high pressure tyres, so that they can be retracted forward of the front spar. The wing has been built in one piece, so that the requirements of maintenance, small transport sizes, and ease of operation from unprepared aerodromes have been sacrificed. Instead, a large saving in weight has been effected by keeping a light and efficient monocoque structure right across the fuselage and by the elimination of heavy wing-to-fuselage joints.

General Problems.

In single-seater fighter design the all-up weight must be kept to a minimum and the use of new materials and methods must always be kept in mind. In control systems and secondary structures the use of Elektron and other light alloy castings is increasing. This considerably simplifies production, as difficult machining problems are thereby removed. Steel castings are also used for highly stressed and complicated parts which are difficult to make by any other means. Cast steels are now available with strengths of over 60 tons/sq. in. which also have good elongation and Izod values.

Hydraulic systems are generally used in British designs to operate flaps and undercarriage. These should be simple to operate and as nearly as possible automatic, as the fighter pilot has many other things to think of. Undercarriage retraction should be as fast as possible (8-10 secs.) as when the undercarriage is down the overall drag of the aircraft is increased by 50 per cent. or more, and the gain in take-off if the undercarriage is retracted immediately after leaving the ground is considerable.

In the F.W. 190 the ancillary services are all electric. A considerable saving in weight is achieved by eliminating the hydraulic and vacuum systems, and

consideration should be given to a change-over in future British designs, if the electrical equipment can be made available. and British electric wiring systems can be simplified.

Both ventilation and heating should be provided in the cockpit. Heating is most easily provided by leading a pipe from behind the radiator matrix into the cockpit, allowing the pilot to control the supply of warm air by means of a valve.

The exhaust system must be designed so that there is no chance of fumes entering the cockpit, and so that the pilot is not blinded by the glare of the exhausts at night.

The pilot must be armour protected against enemy attack from ahead and astern. A bullet-proof windscreen is fitted, and in the case of the Hurricane this windscreen has successfully stopped cannon shells without damage to the aircraft or pilot. The recent heavier armouring of aeroplanes is necessitating the use of heavier and heavier armament. It is the old story of the battleship and the torpedo. Bigger torpedoes of greater penetrating power have resulted in the use of thicker armour. The same thing is happening with the aeroplane. Armour which is proof against 0.303 bullets has forced us to the use of 20 mm. cannons, and an effort will now be made to make the crew and vital parts of aeroplanes proof against 20 mm. fire, when we shall be compelled to use armament of still higher calibre.

Many problems are set up by the purely military requirements, but these cannot be discussed here. The needs of the future are decided between the Air Staff and designers, and they have to forecast accurately the trend of enemy development at least two years ahead. It is their vital responsibility to ensure that our fighters on the drawing board to-day will be superior in speed, climb, and manœuvrability to any enemy fighter which will take the air during the next two to five years, and that their armament will be adequate to deal with enemy aircraft of all types.